Parameterization and Implementation of the Introductory Carbon Balance Model to Model Carbon Sequestration in Soils of Old Growth Forests in Western Pennsylvania.

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Abstract

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Increasing atmospheric carbon dioxide levels have sparked global interest in carbon dioxide sequestration. Carbon sequestration in the earth's soils has been shown to be a large and accessible sink for reducing atmospheric carbon dioxide levels. Determining carbon content already present in soils is as essential to understanding the process of carbon sequestration as modeling how much carbon can be stored in soil in the near future. Soil carbon data from the Tionesta Scenic and Natural Areas of northwestern Pennsylvania was available for four forests ranging from 15 years to 600 years old. Each site was sampled at three depth increments and analyzed with pyrolysis Molecular Beam Mass Spectrometry (py-MBMS), which rapidly characterizes soil carbon content and chemical species. We evaluated many ecological modeling programs for predicting soil carbon dynamics and uptake with time and chose the Introductory Carbon Balance Model (ICBM). Data sets from the four sites comprised of total carbon and amounts of young, intermediate, and old carbon were integrated into the ICBM program to validate its use in modeling forest soil carbon sequestration potential. Preliminary work showed that with more samples and forest soil data, ICBM can and should be used to model forest soil carbon dynamics over a 30-year time frame. Applying this model to our quantitative soil carbon data can further validate its use as a tool to answer questions about sequestering CO_2 in the earth's soils. This sequestration can be a substantial and natural way to reduce global CO_2 levels.

Category: ___Chemistry for BioEnergy Systems______

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1. Introduction

CO_2 Sequestration

As present global carbon dioxide levels increase, the need for carbon sequestration becomes even more critical. The increases in CO_2 levels can be described by the research from Mauna Loa, Hawaii. Mauna Loa is an island volcano isolated from a large human population, so it provides a minimal atmospheric level of CO_2. The Mauna Loa data shows a 17.4% increase in the mean annual concentration of CO_2, from 315.98 parts per million by volume (ppmv) of dry air in 1959 to 370.9 ppmv in 2001 (Keeling and Whorf 2002).

The recent debate about global warming and climate change has sparked interest in research and development of carbon sequestration techniques. Globally, there are three main natural sinks for carbon sequestration, those being the ocean, geologic landforms, and terrestrial ecosystems. Ocean sequestration could involve the direct injection of pure CO_2 into the deep ocean. Another possibility is to increasing the ocean's ability to naturally uptake CO_2 from the atmosphere, but this requires application of iron fertilizers to surface and near surface waters. Due to its immense volume, if the ocean sequestered the amount of carbon needed to double the atmosphere's present concentration, ocean CO_2 concentrations would increase by less than 2% in deep ocean waters. Sequestering CO_2 in geologic formations is already underway offshore in Norway. In an aquifer 1000 m below the sea, CO_2 separated from natural gas is being injected at an approximate rate of one million tons per year. Other potential geologic formations include old oil fields and coal beds (U.S. D.O.E. 1999).

Our research focused on terrestrial sequestration. Sequestering carbon in forest soils is perhaps the least expensive and most natural way to reduce atmospheric CO_2 levels. Recent research using a rapid pyrolysis Molecular Beam Mass Spectrometry (py-MBMS) technique and a multivariate statistical approach has revealed four groups of carbon species naturally occurring in the old growth forest soils of northwestern Pennsylvania. Two of those components were identified, one as 'recent' carbon and the other as 'older' carbon (Magrini et. al. 2002). In that paper, the authors left an invitation for the future modeling of their characterized forest soils as a way to monitor forest carbon sequestration.

Modeling Carbon Sequestration

Before forest soils are implemented to sequester atmospheric carbon dioxide, research must show that a substantial amount of sequestration can take place. To do this, researchers use ecological models to model carbon dynamics in a variety of environments. Some of the more common carbon dynamics models include CENTURY, ROTH-C, NCSOIL, ICBM, SOMM, and many others. A variety of these types of ecological models were evaluated to determine which would best suit the purpose of our research. Models were mainly evaluated on the basis of input and output variables. We chose a model developed by Olof Andrén and Thomas Kätterer to predict soil carbon dynamics in Swedish agricultural land. The Introductory Carbon Balance Model (ICBM) is easily adaptable to any environment, and utilizes a minimal number of variables, that are shown in Table 1. This version of the model assumes that just two groups can describe soil carbon: young and old carbon. The second assumption is that each of these pools has a decomposition rate that follows first-order kinetics. The next assumption is that annual carbon input is explained by one variable, i. The last assumption is that climatic and external influences are all defined by one variable, r_e (Andrén and Kätterer 1997). A schematic diagram of the model is presented in Figure 5 (Kätterer and Andrén 2001). In our research we were not trying to model carbon sequestration, but rather trying to validate the application of ICBM to model forest soil dynamics.

Tionesta Natural and Scenic Area

To validate our model, a chronologically sampled data set was needed. The United States Forest Service provided us with forest soil samples taken from four sites at three depths. These samples represented a 600-year snapshot of natural carbon sequestration. Each forested area began as beech hemlock and experienced a wind disturbance at approximately 150-year intervals that provided different aged forests within close proximity of each other. These sites provided us with a chronological map of forest soil carbon changes that we could analyze and quantitate with mass spectrometry. The four sites, 1985 blowdown, 1872 blowdown, 1808 blowdown, and Virgin Beech Hemlock (VBH), represented forests with increasing time since a major disturbance, in this case tornadoes. The 1985 site was 15 years old since the last disturbance, the 1872 site being 128 years old, the 1808 site at 177 years, and the VBH site being estimated at 600 years old. The four different sites were normalized and treated as one site, with soil carbon measurements at time 0 (1985 blowdown), 113 years (1872 blowdown), 177 years (1808 blowdown), and 585 years (VBH).

2. Materials and Methods

Parameterization of the Model

The four SOM components identified and characterized through a rapid py-MBMS technique served as a basis of our data for the model (Magrini et. al. 2002). The other part of the data came from total carbon content values (MT/ha) for the same forest (Hoover et. al. 2001). The fractional values for components 1, 2, 3, and 4 of sample soil organic matter (SOM) were multiplied with the corresponding amount of carbon for each depth and site (C. Hoover, personal communication, July 15, 2002) to gain an amount of each component, at each depth, at each of the four sites. All component values were then converted to kg/m², the working units of ICBM. In order to use this component data in ICBM, the score for component 3 was used for young carbon (Y_o), and scores for components 1, 2, and 4 were combined to determine the value of old carbon (O_o). The newly converted data was then grouped by depth, and each depth treated as an individual site.

Using two different sources for data also required the combination of two different confidence intervals. These confidence levels were combined using Formula 1 to give us a statistical confidence measurement for our new data sets.

For preliminary investigations, the annual carbon input parameter of ICBM, i, was optimized. The decomposition rate of 'young' carbon, k_y; the humification quotient, h; and the external response value, r_e; were also optimized using the macros built in to ICBM. The decomposition rate of 'old' carbon was left at a universal constant of .006 kg/m^2/yr (Andrén and Kätterer 2001).

Optimization of Variables

The variables of the ICBM model can be optimized either by solving for predetermined results, or by optimizing parameters to fit the data. Both of these processes are described in the program itself. To optimize the parameters to our site, we first had the program optimize i and k_y by minimizing the error sum of squares of the measured Y values, using the solver tool built into the spreadsheet. Next, h was optimized using the same technique but minimizing the error sum of squares for the measured *O* values. After those optimizations, the error sum of squares was minimized by optimizing r_e. This entire process was repeated for each run of the model.

3. Results

The fractional value for each of the four components in soil organic matter (SOM) for each depth increment are plotted against time and shown in Figures 1-4. These data had not been represented this way before, and once they were plotted we were able to analyze their behavior as a function of time and depth. These analyses helped us determine the fates of components one and four in the model.

ICBM modeled carbon sequestration as naturally shown by our old growth forests in northwestern Pennsylvania. As mentioned earlier, the purpose of this research was to validate ICBM's application to forest soils, that validation is represented in Figure 9. Total carbon, 'young' carbon, and 'old' carbon values for each run of the model were added together along with the corresponding measured values for each site and depth. The modeled value for each falls well within the confidence interval for the measured value.

Amounts of 'young', 'old', and total carbon were modeled for each site (time) and depth. ICBM modeled carbon sequestration best in the 0-5 cm interval, with correlation values of 0.71599, 0.93525, and 0.88952 for 'young', 'old', and total carbon. Each of the graphs demonstrated that carbon is naturally being sequestered in the form of 'old' carbon.

A description of the measured and optimized parameter values for each of the runs in ICBM is presented in Table 2. Our preliminary investigations showed that as depth increases, the humification constant showed a general increase from .009 to .055. The value for input, *i,* showed a large decrease in value as depth increased, matching our expectations. The decomposition rate of 'young' carbon, k_y, stayed constant at 1.115 for all intervals.

4. Discussion and Conclusions

Utilizing only four measurements contributed a large source of error and uncertainty to our modeling process. In reviewing the confidence intervals represented by error bars in Figures 1-4, significant uncertainty is associated with our initial measurements. The main source of this uncertainty may be that the amounts of total carbon used in determining the amount of each factor, came from a very small data set, with the number of samples being either 5, in the 0–5 cm interval, or 4 for the 5–15 cm and 15–30 cm intervals (C. Hoover, personal communication, July 15, 2002). Even with the large amounts of uncertainty, some intervals do not overlap, indicating that the measurements are significantly and statistically different.

In the parameterization of our data for modeling purposes, components 1, 2, and 4 were combined and modeled as 'old' carbon. Component 1 contributed a minimal amount to the total soil carbon content, averaging 4%. On the other hand, component 4 represented a substantial amount of the soil organic matter, representing, on average, 51% of the soil carbon content. The identification of these unknown components is crucial to understanding soil carbon dynamics. Perhaps these two components represent some sort of 'intermediate' carbon specie(s). Research still needs to be done in this area. ICBM does offer more complex models that utilize more carbon pools, but the question still remains as to where these components belong.

ICBM is set up to simulate carbon dynamics of a site 30 cm in depth and it assumes that the value of each variable remains constant as depth increases. However, the data presented by Hoover et al. (2001) and Magrini et al. (2002) suggests that as depth increases, the physical nature of carbon is changing. For example, it is assumed that as depth increases carbon input, i, is decreasing, but ICBM leaves this parameter constant for a 0–30 cm interval. Likewise, as depth increases decomposition rates change in relation to microbe abundance, water availability, oxygen levels, etc. Again, ICBM keeps the decomposition rates, k_y and k_o, constant at all depths. As shown in Table 2, our parameters did vary by depth, just as expected. One reason for variability in our optimized values for input in each interval is that the interval increases from 5 cm, to 10 cm, to a final increment of 15 cm. This is the way soil samples were taken at this site, and this error source could not be avoided. The humification constant represents the fraction of 'young' carbon that degrades into 'old' carbon. Other research presented indicates that the value of h should range from .125 to .3 (Andrén and Kätterer 1997). Perhaps with less optimization of other variables (i, and k_y), this parameter may fall into that range.

The 0-5 cm interval provided the most accurate fit for each of the carbon pools, represented in Figure 5. ICBM had the least success modeling soil dynamics in the middle interval, 5-15 cm. This may be because that depth increment represents an increment where the most humification is occurring.

Figure 2 shows that the data points for the 1872 and 1808 sites appear to be very low. We concluded that without other data to compare these measurements to and with such a small sample size, we cannot determine if these measurements are anomalies or true indications of SOM dynamics.

The validation of ICBM for modeling forest soil carbon dynamics is justifiable with these results. The modeled values for each site fall within the corresponding confidence intervals, but those intervals are relatively large. These intervals also came from the same small data set, which contributes a lot to the large confidence interval. The United States Forest Service and the National Renewable Energy Laboratory are currently working on collecting and analyzing more soil samples from a variety of forests within the United States with much larger sample sizes. Research is currently being done to see if the results published by Magrini et. al. 2002, can be reproduced again, and that these four components of SOM are not unique to the forest studied in that work. Upon completion of this analysis, the new data should be parameterized and used to validate the application of ICBM to forest soils. Future research should also include litter bag data or carbon-14 experiments to determine the parameters, h, k_y, and k_o. Carbon input, i, can be measured, and if this data was available, less optimization would be required, further validating ICBM's application. With this further parameterization, researchers could then confidently use ICBM to model carbon dioxide sequestration in forest soils.

5. Acknowledgements

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7. Figures and Tables

Table 1. Description of variables associated with ICBM from Katterer and Andren (2001).

Parameter	Dimension	Description
Y_o	kg	Initial C mass of 'young' pool
O_o	kg	Initial C mass of 'old' pool
i	kg/yr	Annual C input to soil
k_y	Per year	Decomposition rate constant for the 'Young' pool
k_o	Per Year	Decomposition rate constant for the 'Old' pool
h	Dimensionless	Humification quotient: fraction of 'Young' out flux that enters 'Old'
r_e	Dimensionless	External response: factor that affects flux from 'Young' and 'Old'

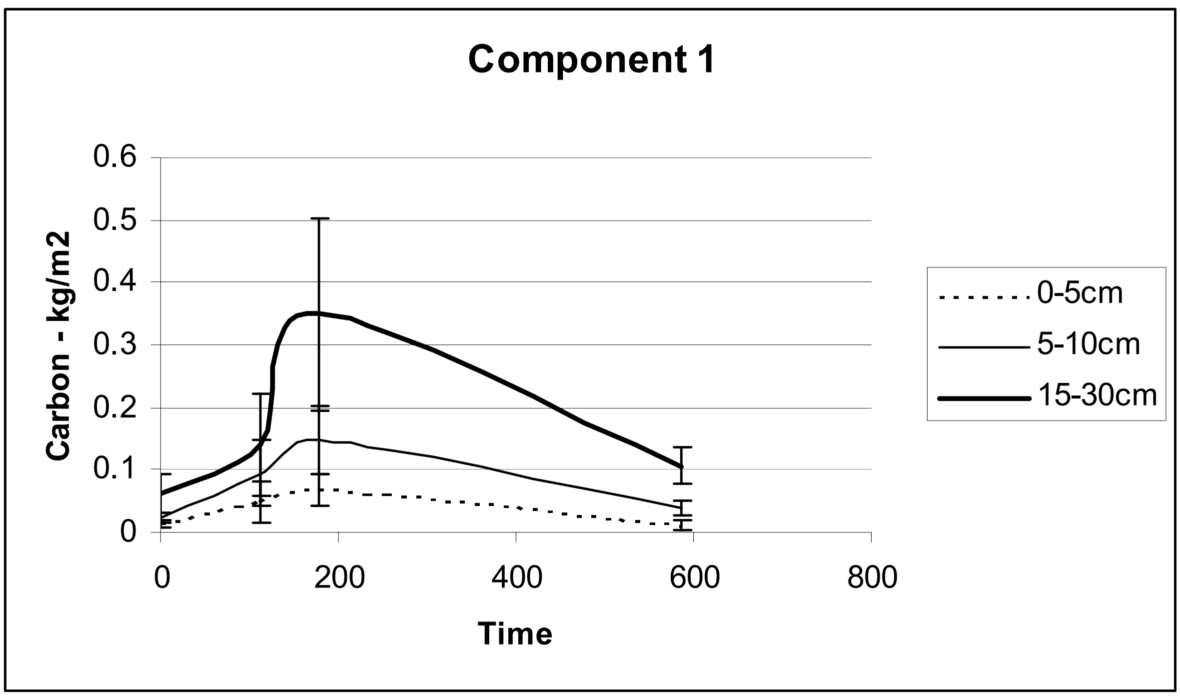

Figure 1. Component 1 of SOM identified in factor analysis by Magrini et. al. 2002.

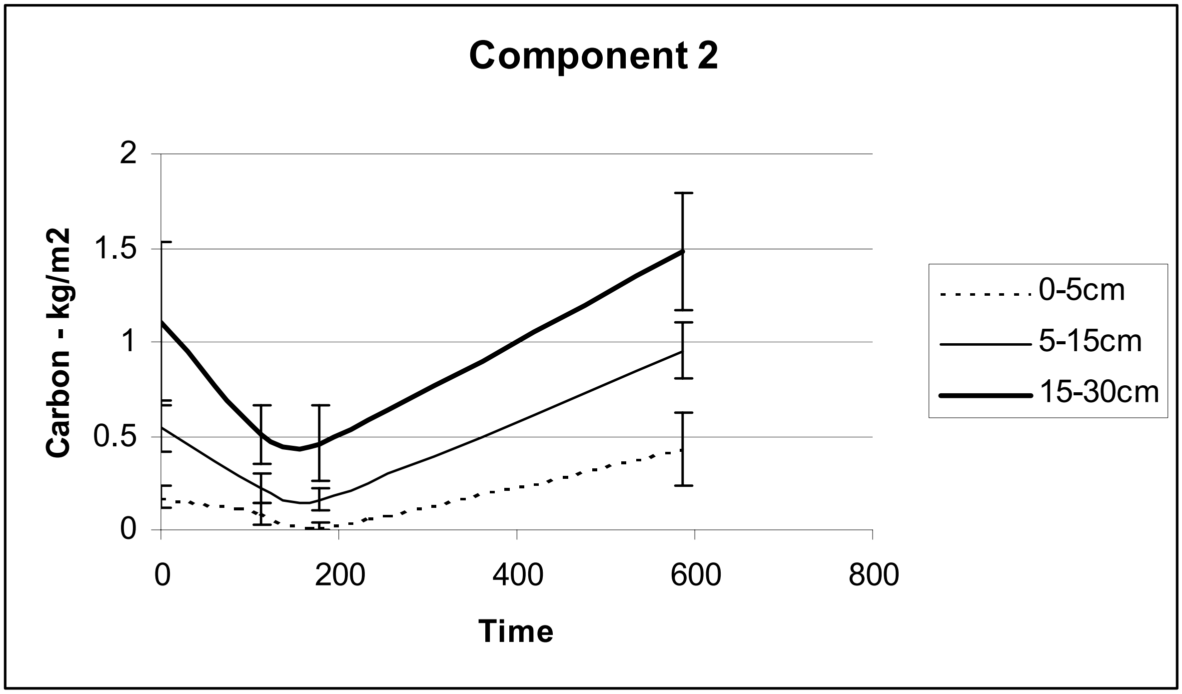

Figure 2. Component 2 of soil organic matter, identified as 'old' carbon by Magrini et. al. 2002. The component amounts are plotted for each depth as a function of time.

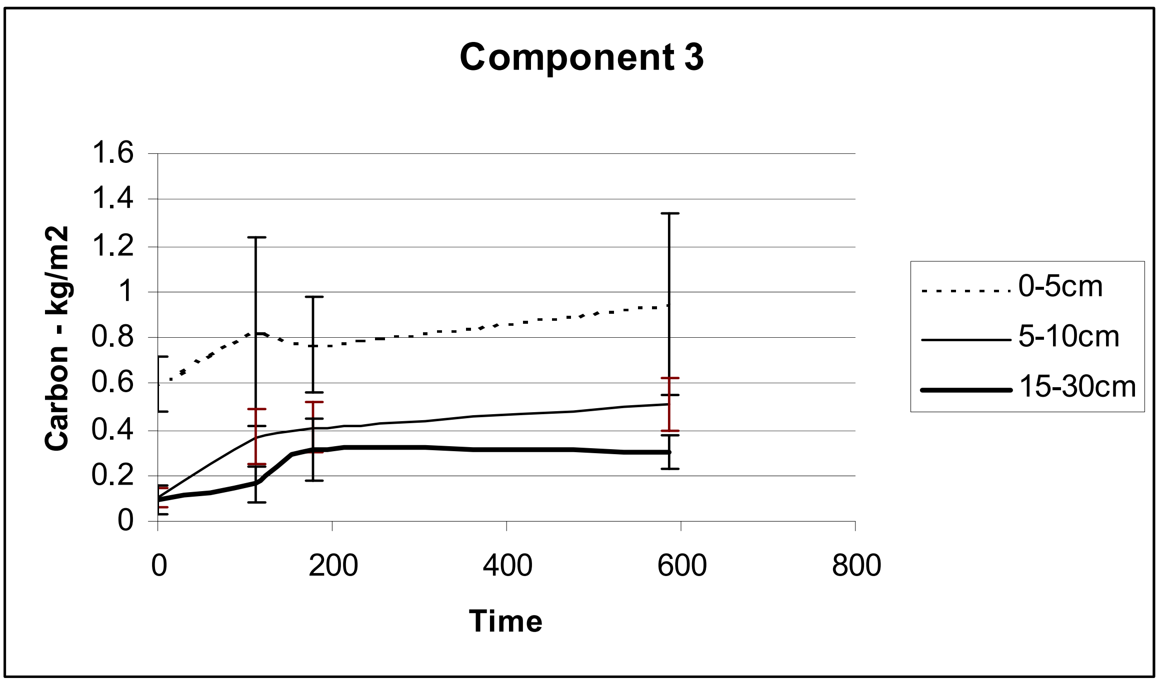

Figure 3. Component 3, identified as 'recent' carbon by Magrini et. al. 2002.

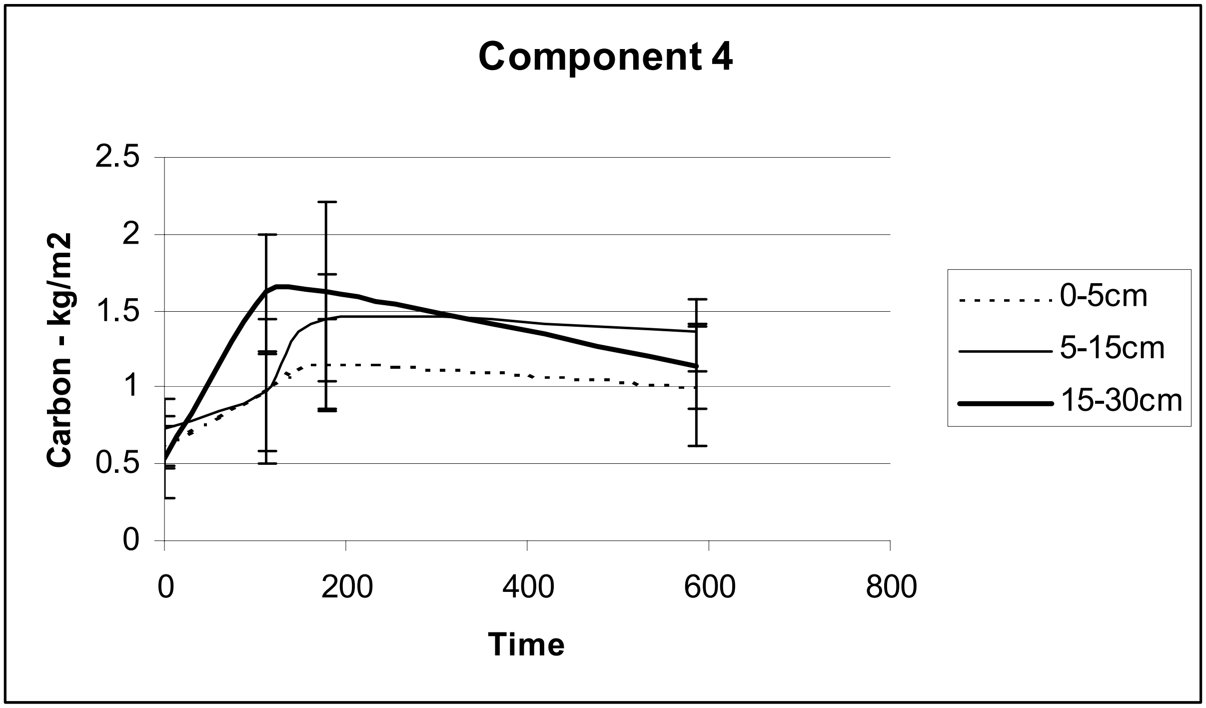

Figure 4. Component 4 of soil organic matter identified by Magrini et. al. 2002. Component values are plotted for each depth and plotted against time.

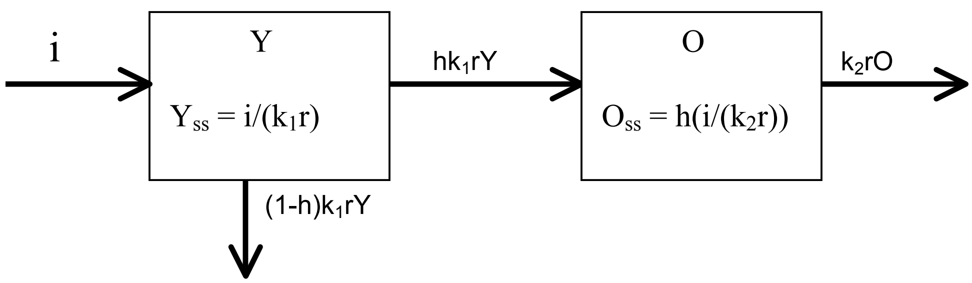

Figure 5. ICBM flow chart from Katterer and Andren (2001). Refer to Table 1 for an explanation of variables.

$$\boxed{\Delta x = uv\{(\Delta u/u) + (\Delta v/v)\}}$$

Formula 1. Algebraic formula used to determine confidence interval (Δx) of combined data sets, u and v with their own confidence intervals, Δu and Δv.

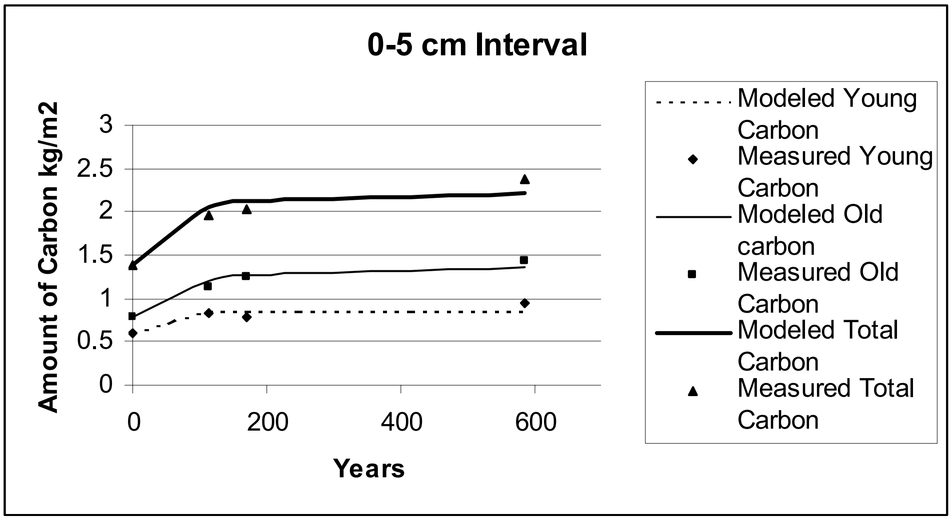

Figure 6

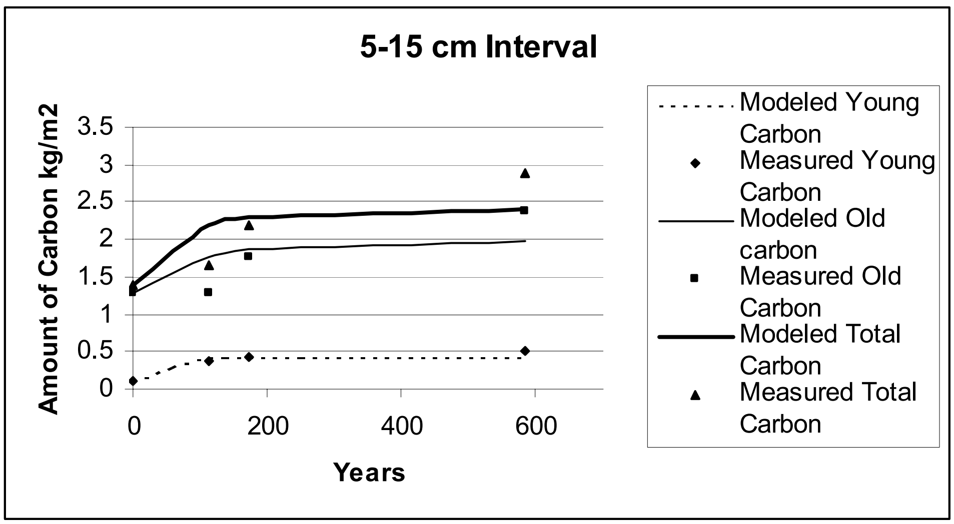

Figure 7

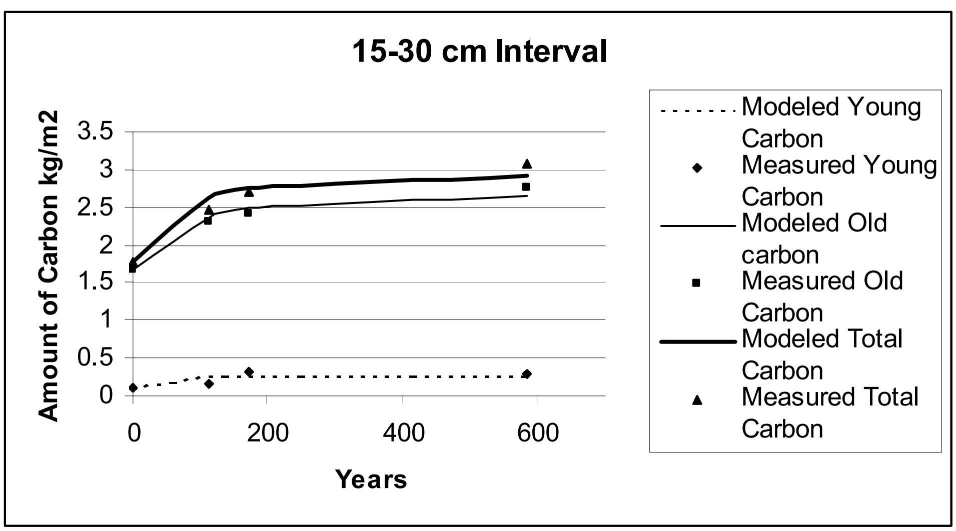

Figure 8.

Figures 6-8. These graphs show the comparisons between the modeled values for soil carbon by ICBM and the measured values. Each depth increment was treated as a different site with different parameter values

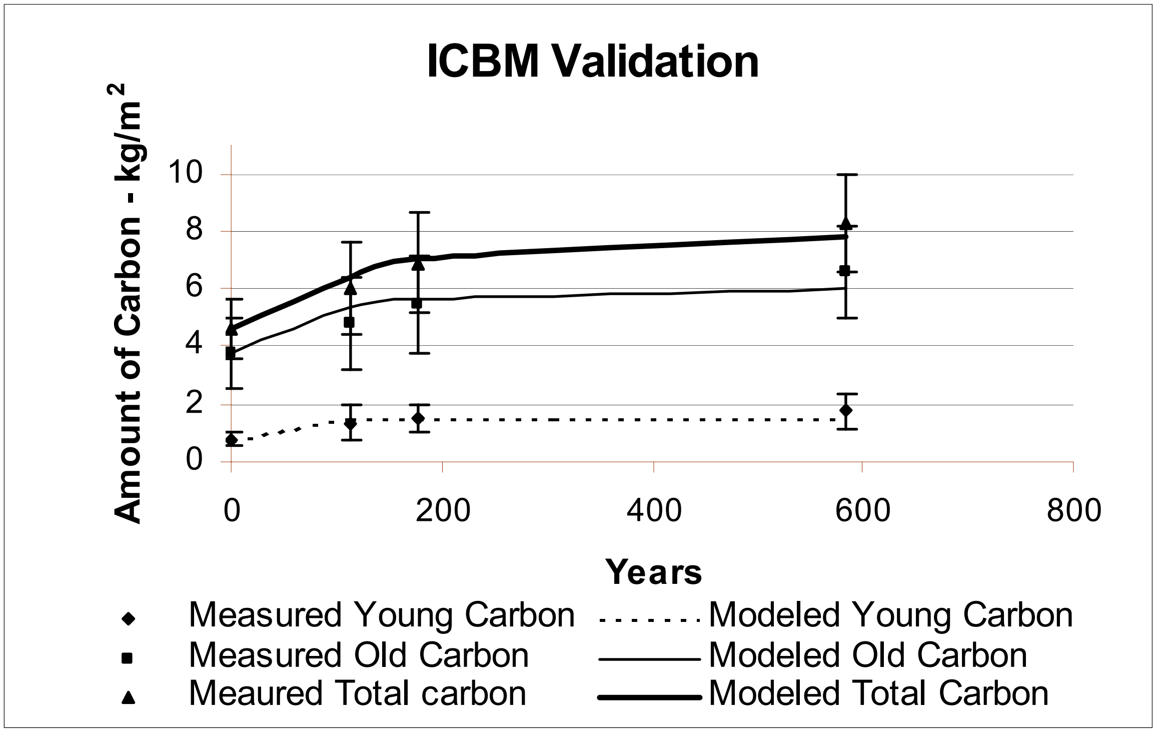

Figure 9. A graph representing the measured values of total carbon and the predicted values from ICBM. Error bars represent error in measurement of total carbon, young, and old carbon.

Table 2. An optimized or measured value for each of the parameters, in each trial/depth interval is shown. *Denotes optimized parameter.

Parameters	Dimensions	0-5cm	5-15cm	15-30cm
Y_o	kg/m^2	.59275	.10619	.09352
O_o	kg/m^2	.79592	1.27975	1.68331
*i	kg/m^2/yr	1.716	.871	.523
*k_y	Per year	1.115	1.115	1.115
k_o	Per Year	.006	.006	.006
*h	Dimensionless	.009	.025	.055
*r_e	Dimensionless	1.808	1.808	1.808